RT Modelling of CMEs Using WSA-ENLIL Cone Model

2014-06-04

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In this presentation we will make an introduction to the WSA-ENLIL Cone model, used at SWRC to model propagation of coronal mass ejections (CMEs) in the heliosphere.

Outline

- Basic Principles behind cone modeling of CMEs.
- Brief description of the models
- Analyzing CME propagation and impact
- Operations example: collaboration with AFWA

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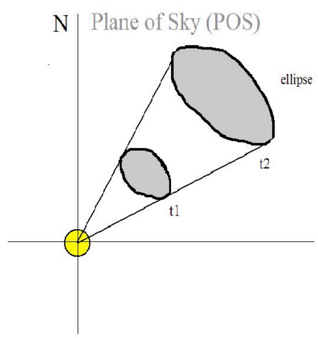
First, I will say few words about basic principles behind cone modeling of CMEs.
Then, I will make a brief description of the WSA and ENLIL models.
After that I will describe how we analyze CME propagation and it's impact
Finally, I will demonstrate an example of forecasting in operations:
A collaboration with Air Force Weather Agency (AFWA)

Cone Model for CMEs



The projection of the cone on the POS is an ellipse

Zhao et al, 2002, Cone Model:

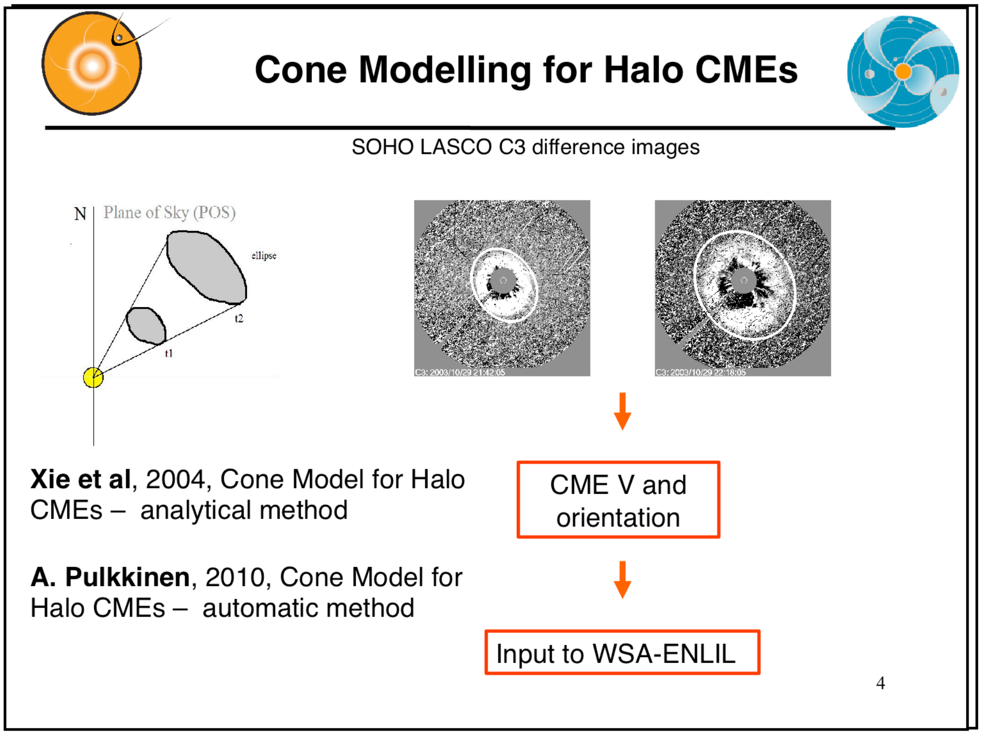
The CME cone model is based on observational evidence that CME has more or less constant angular diameter in corona, being confined by the external magnetic field, so that CME does not expand in latitude in the lower corona, but expands in interplanetary space because of the weaker external field

- CME propagates with nearly constant angular width in a radial direction
- CME bulk velocity is radial and the expansion is isotropic

Overly simplistic approximation to describe halo CME

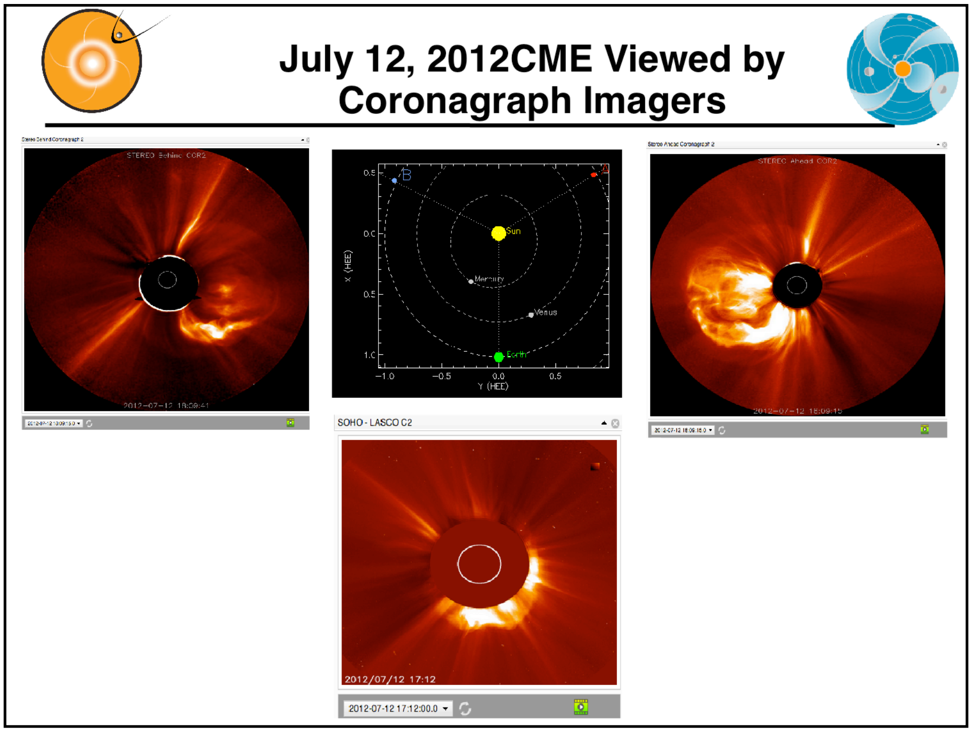
Zhao was the first to come up with the Cone model of CME. The CME cone model is based on observational evidence that CME has more or less constant angular diameter in corona, being confined by the external magnetic field, so that CME does not expand in latitude in the lower corona, but expands in interplanetary space because of the weaker external field. The assumptions are the following:

- CME propagates with nearly constant angular width in a radial direction
- CME bulk velocity is radial and the expansion is isotropic



CME and its motion in the interplanetary space can be observed in the coronograph images. Coronographs create an artificial eclipse of the Sun. Eclipses allow corona to be better viewed. But natural eclipses do not happen often. Occulting disk blocks the bright sun so we can observe coronal features. Shown in this slide are difference images.

Xie et al, 2004, developed analytical method of defining Cone Model CME parameters for Halo CMEs. A. Pulkkinen , 20010 developed automatic method of defining Cone Model CME parameters for Halo CMEs.

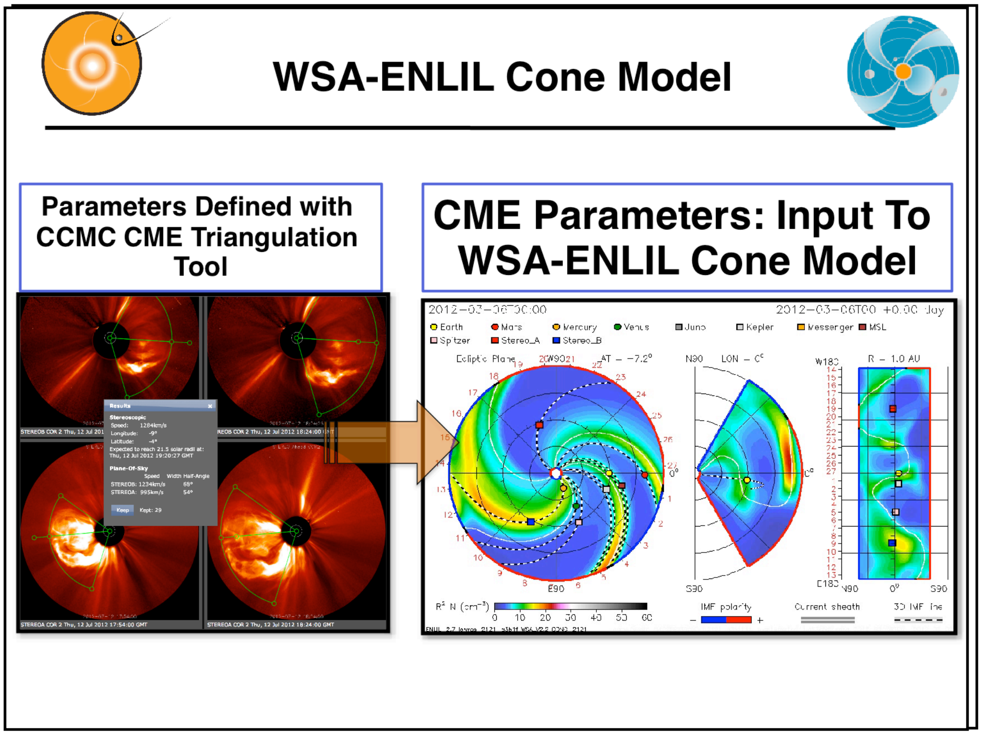


Another method to derive Cone model parameters is triangulation method.

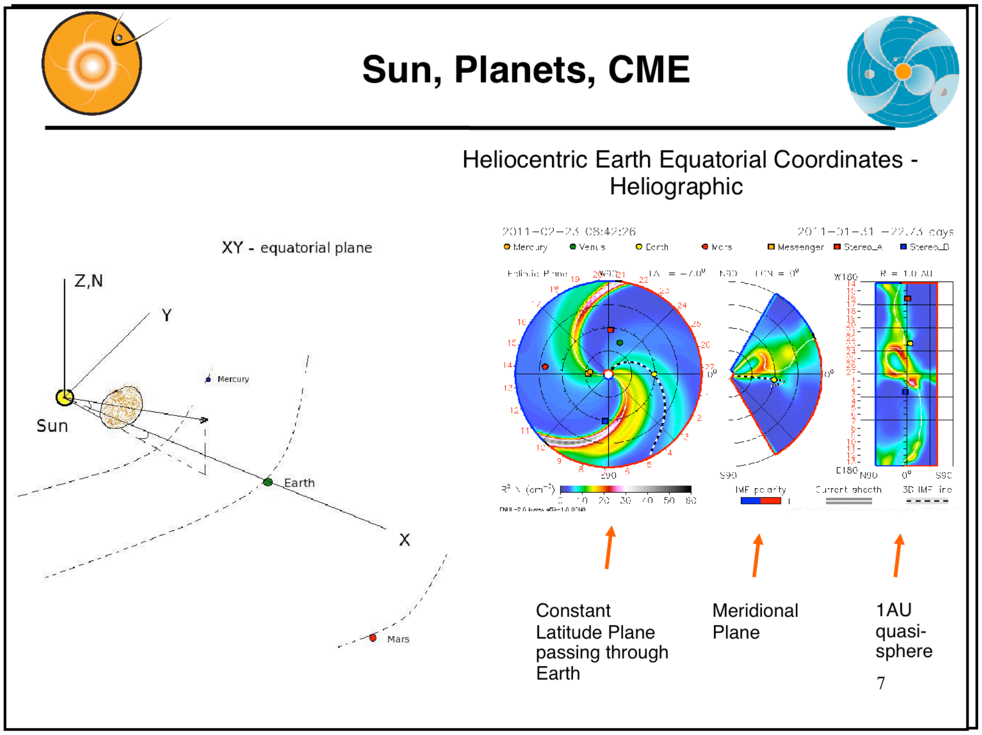
This slide shows the a CME seen in 3 coronographs located on three different satellites.

The schematic in the upper center shows the location of STEREO B, SOHO and STEREO A satellites in the ecliptic plane at the time when the CME occurred.

The CME was moving sort of towards the Earth, so STB sees it moving to the right in its plane of sky, for STA it moves to the left and it’s a halo image for SOHO that is located on a sun-earth line.



Parameters defined with CCMC CME Triangulation Tool (CAT) or other tools are used as input CMEpParameters to WSA-ENLIL Cone Model.

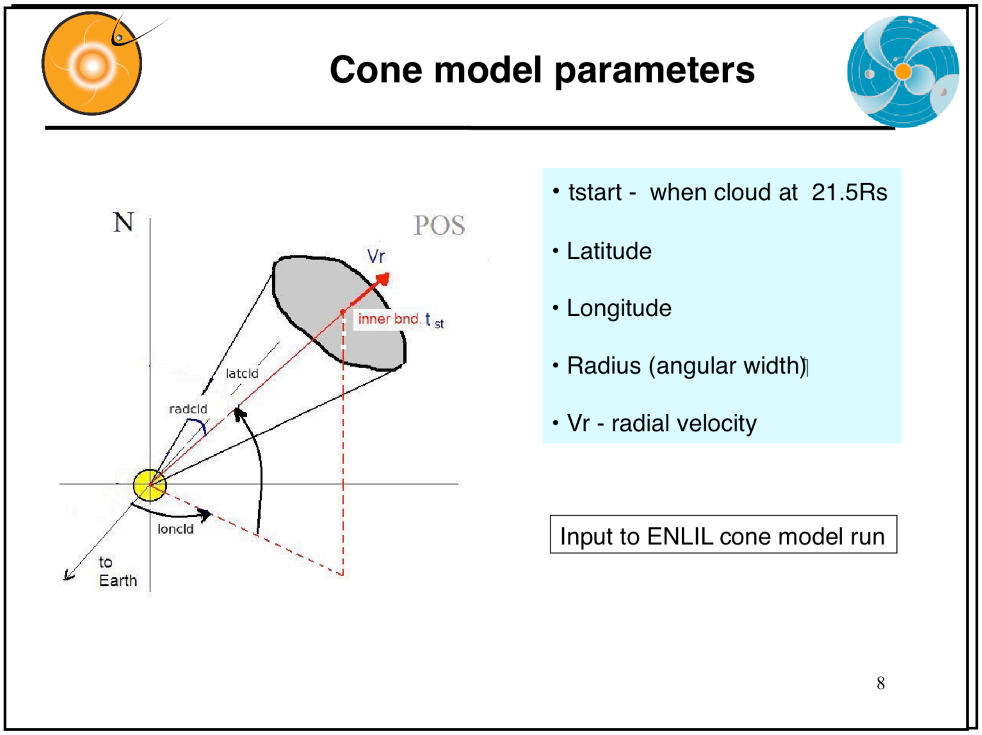


This schematic shows CME in global perspective and explains coordinate system of the WSA-ENLIL model.

XY is the equatorial plane (plane of the Sun equator). Z axis points to to north pole of the Sun. Earth is located in the ecliptic plane, which forms some variable angle with the equatorial plane (changes from -7.5 deg to 7.5 deg).

The first panel in WSA-ENLIL plot shows a plane passing through the Earth and is parallel to equatorial plane. The second panel is a meridianal cut passing through the Earth. The latitude goes from -60 to 60 degrees.

The third panel shows Longitude-Latitude map of a quasi sphere at 1 AU and with The cut off for Latitude > |60 deg| .



Parameters defined with CCMC CME Triangulation or other Tools yield CME Parameters: Input To WSA-ENLIL Cone Model. These parameters are:

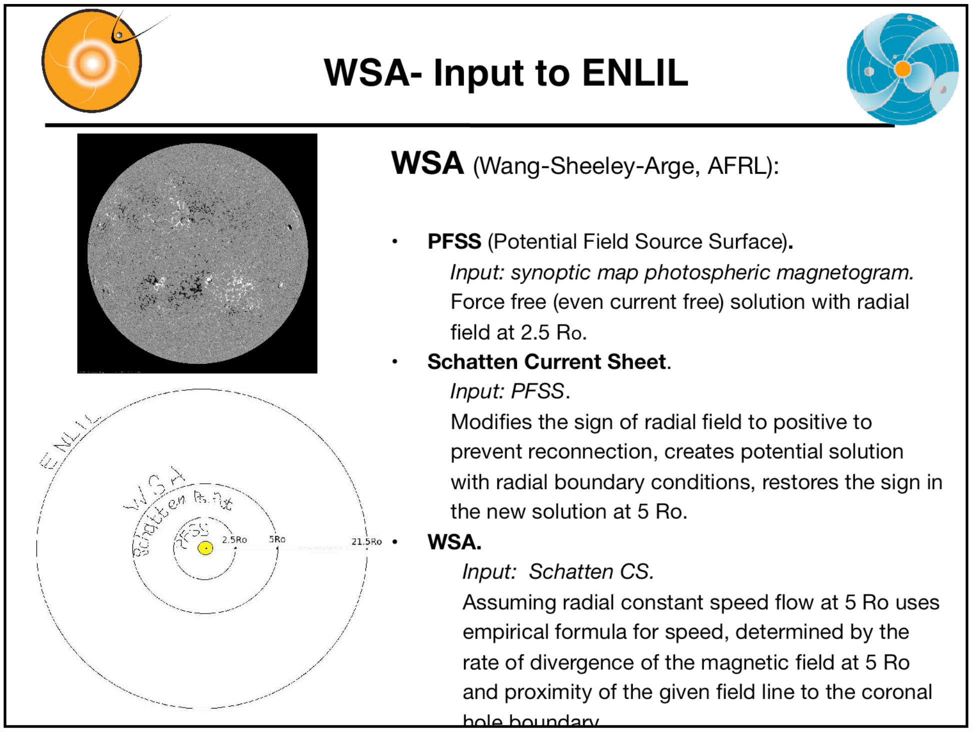
1- start time of CME at 21.5 Rs (inner boundary of the ENLIL model)

2- Cone axis latitude

3- Cone axis longitude

5- Cone Radius – half angle of the cone angular width

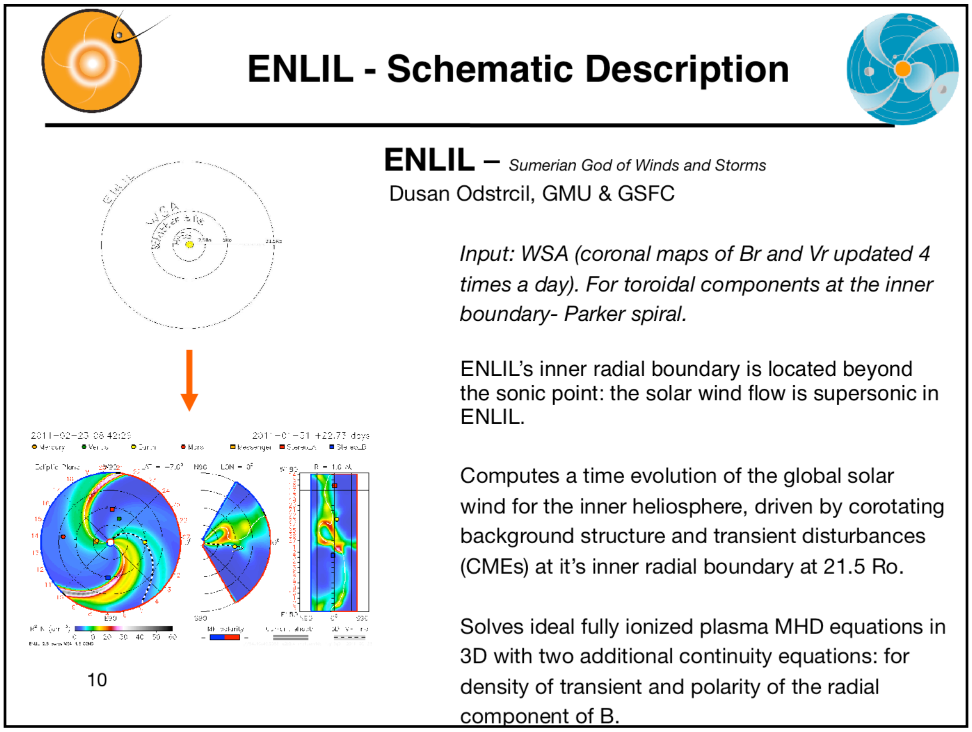
6- Radial Velocity



Wang-Sheeley-Arge model WSA (Wang-Sheeley-Arge, AFRL)
is the input model to the ENLIL at it's inner boundary of 21.5Rs.
The input to the WSA is daily magnetograms of the solar surface, that describe the magnetic field of the photosphere.

WSA model itself consists of different models

- **PFSS** (Potential Field Source Surface).
  Input: synoptic map photospheric magnetogram.
  Force free (even current free) solution with radial field at 2.5 Ro.
- **Schatten Current Sheet**.
  Input: PFSS.
  Modifies the sign of radial field to positive to prevent reconnection, creates potential solution with radial boundary conditions, restores the sign in the new solution at 5 Ro.
- **WSA.**
  Input: Schatten CS.
  Assuming radial constant speed flow at 5 Ro uses empirical formula for speed, determined by the rate of divergence of the magnetic field at 5 Ro and proximity of the given field line to the coronal hole boundary.



ENLIL – Sumerian God of Winds and Storms

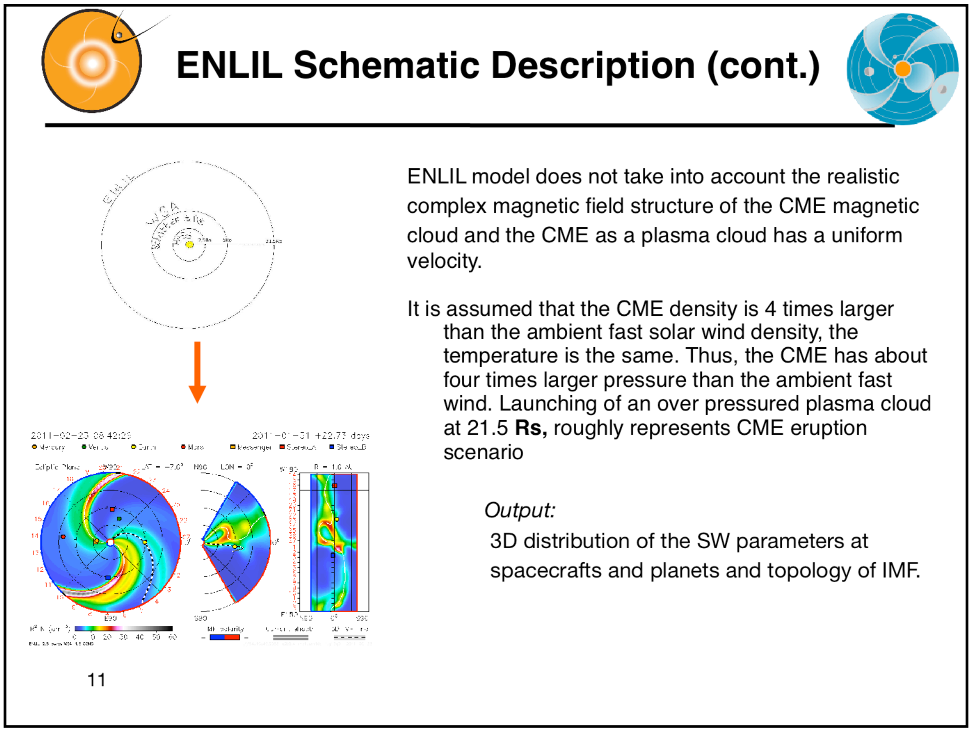
Dusan Odstrcil, GMU & GSFC

Input: WSA (coronal maps of Br and Vr updated 4 times a day). For toroidal components at the inner boundary- Parker spiral.

ENLIL's inner radial boundary is located beyond the sonic point: the solar wind flow is supersonic in ENLIL.

Computes a time evolution of the global solar wind for the inner heliosphere, driven by corotating background structure and transient disturbances (CMEs) at it's inner radial boundary at 21.5 Ro.

Solves ideal fully ionized plasma MHD equations in 3D with two additional continuity equations: for density of transient and polarity of the radial component of B.



Limitation of the ENLIL model:

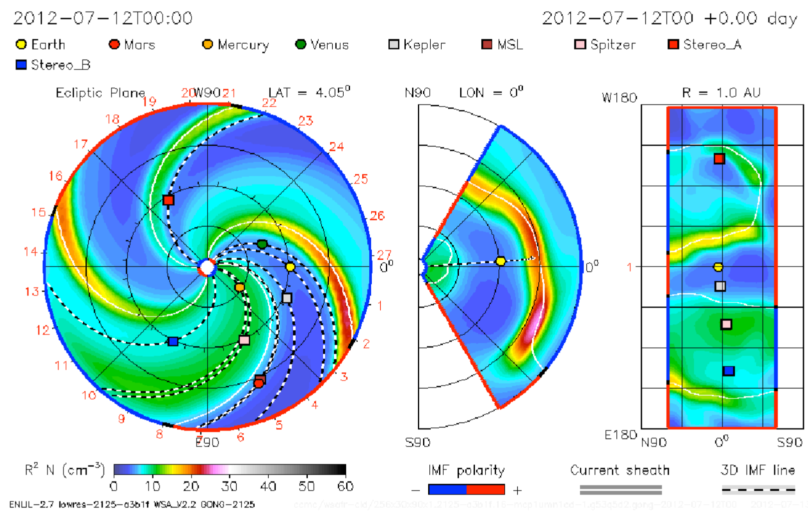
It does not take into account the realistic complex magnetic field structure of the CME magnetic cloud and the CME as a plasma cloud has a uniform velocity.

It is assumed that the CME density is 4 times larger than the ambient fast solar wind density, the temperature is the same. Thus, the CME has about four times larger pressure than the ambient fast wind. Launching of an over pressured plasma cloud at 21.5 **Rs,** roughly represents CME eruption scenario

Output:

3D distribution of the SW parameters at spacecrafts and planets and topology of IMF.

CME modeling



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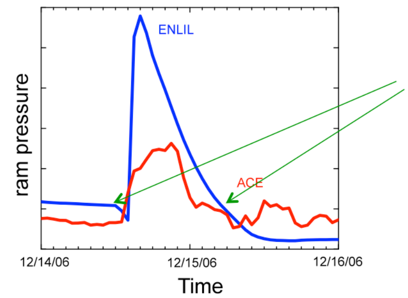
After we define the CME parameters we run the WSA-ENLIL cone model.

CME Impact – arrival, duration, MP standoff distance

CME shock arrival – a sharp jump in the dynamic pressure



Duration of the disturbance – duration of the dynamic pressure hump

Magnetic field required to stop SW

$$\frac{B_{stop}^2}{2\mu_0} = Knm_pV^2$$

Magnetopause standoff distance

$$\frac{r_{mp}}{R_e} = \left(\frac{B_0}{B_{stop}}\right)^{1/3}$$

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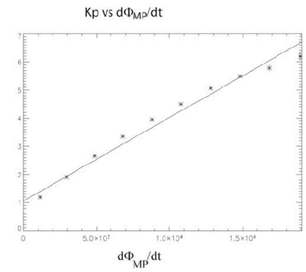
After the run is done, we estimate the CME impact on planets, satellites.

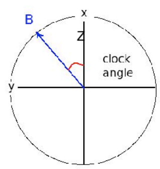
1. CME shock arrival – a sharp jump in the dynamic pressure.
2. Duration of the disturbance – duration of the dynamic pressure hump.
3. In case of the Earth we estimate also the degree of compressing of the magnetosphere: when the CME mass reaches the magnetosphere it pushes it inward and the magnetic field of the Earth is stressed like a spring to stop the CME motion.

Kp Index – P. Newel's Empirical Expression

Magnetic flux opening
rate at the magnetopause

$$\frac{d\Phi_{MP}}{dt} = V^{4/3} B^{2/3} \sin^{8/3}(cl\,ang/2)$$





$$Kp = 1 + 0.0002947 \frac{d\Phi}{dt}$$

$$Kp = 9.5 - \exp\left(2.17676 - 0.000052001 \frac{d\Phi_{MP}}{dt}\right)$$

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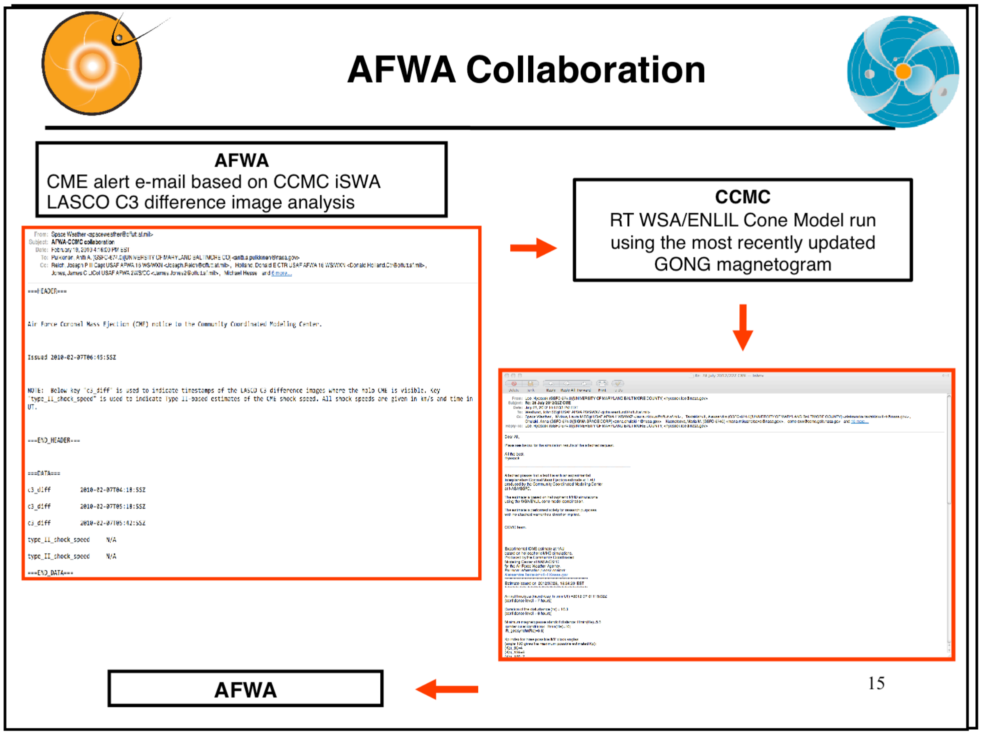
In case of the Earth we estimate also the Kp index – a measure of the disturbance of the magnetosphere.

We use Pat Newel's empirical formula for the Magnetic flux opening rate at the magnetopause for that and an empirical relation between Kp and d(Phi)/dt.



I will end with an example of operational setup of our cone modeling in collaboration with the Air Force Weather Agency.

1. First we get AFWA CME alert e-mail based on CCMC iSWA
LASCO C3 difference image analysis (unlike us, who are not
really an operational center, AFWA is monitoring 24/7 the Space Weather
and Sun.
2. We perform WSA-ENLIL modeling of the requested CME(s) and send t
3. hem back the CME impact assessment e-mail.

AFWA Collaboration 2

AFWA e-mail

From: Space Weather <spaceweather@offutt.af.mil>
Subject: **AFWA-CCMC collaboration**
Date: February 19, 2010 4:16:00 PM EST
To: Pulkkinen, Antti A. (GSFC-674.0)[UNIVERSITY OF MARYLAND BALTIMORE CO] <antti.a.pulkkinen@nasa.gov>
Cc: Reich, Joseph P III Capt USAF AFWA 16 WS/WXN <Joseph.Reich@offutt.af.mil>, Holland, Donald E CTR USAF AFWA 16 WS/WXN <Donald.Holland.Ctr@offutt.af.mil>, Jones, James C LtCol USAF AFWA 2WS/CC <James.Jones2@offutt.af.mil>, Michael Hesse and 6 more...

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===HEADER===

Air Force Coronal Mass Ejection (CME) notice to the Community Coordinated Modeling Center.

Issued 2010-02-07T06:45:55Z

NOTE:  Below key "c3_diff" is used to indicate timestamps of the LASCO C3 difference images where the halo CME is visible. Key
"type_II_shock_speed" is used to indicate Type II-based estimates of the CME shock speed. All shock speeds are given in km/s and time in
UT.

===END_HEADER===

===DATA===
c3_diff         2010-02-07T04:18:55Z
c3_diff         2010-02-07T05:18:55Z
c3_diff         2010-02-07T05:42:55Z
type_II_shock_speed     N/A
type_II_shock_speed     N/A
===END_DATA===
```

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Here is AFWA-s e-mail in detail. The indicate the instrument and time stamps of the coronograph images when the CME that was observed.

AFWA Collaboration

Estimate e-mail

Arrival time(year/month/day, hr:min UT) =2012-07-31T15:02Z
(confidence level +-7 hours)

Duration of the disturbance (hr) = 10.3
(confidence level +-8 hours)

Minimum magnetopause standoff distance: Rmin(Re)=5.6
(under quiet conditions: Rmin(Re)=10;
R_geosynchr(Re)=6.6)

Kp index for three possible IMF clock angles
(angle 180 gives the maximum possible estimated Kp):
(Kp)_90=4
(Kp)_135=6
(Kp)_180=7

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Here are the links to the movies of the modeled event

http://iswa.gsfc.nasa.gov/downloads/20120729_014700_afwa_anim.tim-den.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_afwa_anim.tim-vel.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_afwa_anim.tim-pdyn.gif

Inner Planets
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-den.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-vel.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-den-Stereo_A.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-vel-Stereo_A.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-den-Stereo_B.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-vel-Stereo_B.gif

Timelines
http://iswa2.ccmc.gsfc.nasa.gov/downloads/20120729_014700_ENLIL_CONE_timeline.gif
http://iswa2.ccmc.gsfc.nasa.gov/downloads/20120729_014700_ENLIL_CONE_Kp_timeline.gif

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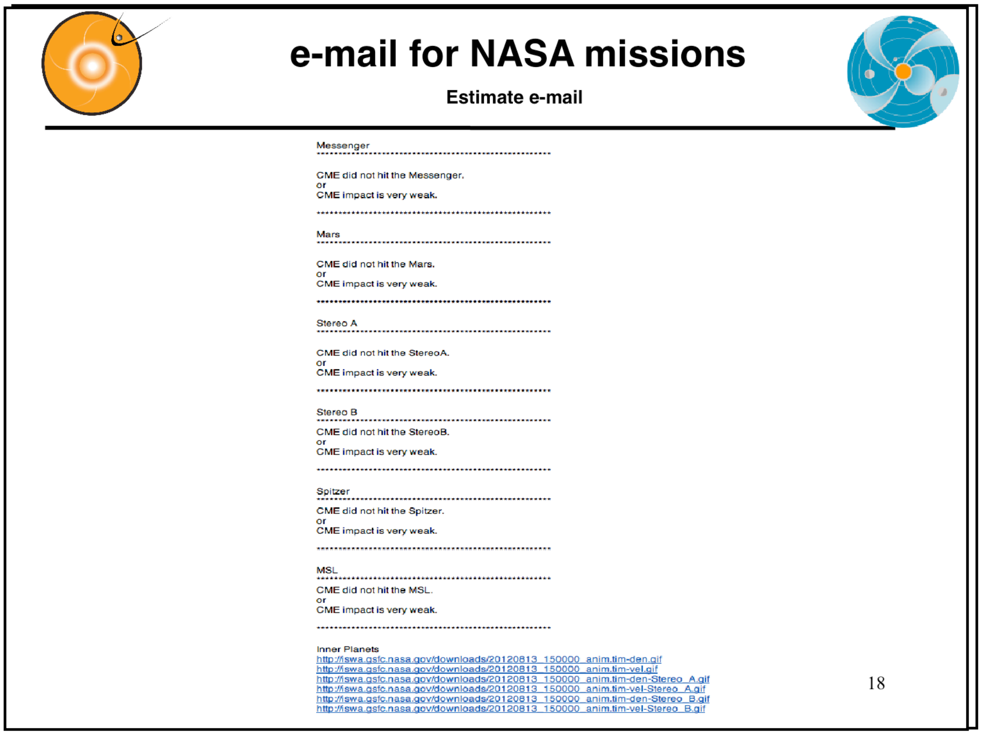
And here is our response e-mail the them in details.
It contains the CME impact estimate for the Earth
(arrival time, magnetopause standoff distance,
Kp estimate for three possible clock angles of the IMF),
and links to the modeling animation and timelines.



But we are not monitoring only Earth impact. Being responsible for providing space weather assessment to NASA robotic mission operators, we are monitoring possible impact of the CME on NASA missions.
So we send out another e-mail, that shows this estimate.